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Aging Monitoring of Bond Wires Based on EMR Signal Spectrum Characteristics for IGBT Module

Zhihui Ren[1], Mingxing Du[1, *], Jinliang Yin[1], Chao Dong[1], and Ziwei Ouyang[1, 2]

Abstract—Bond wires aging is one of the most common failure modes of insulated gate bipolar transistor (IGBT) module. Real-time monitoring of bond wires status is an important guarantee for the stable operation of power electronics system. In this paper, a method of monitoring the aging state of bond wires in IGBT module based on the spectrum characteristics of electromagnetic radiation (EMR) signature is proposed. Firstly, the turn-off process of IGBT module is analyzed, and the behavior model of IGBT module in the stage of rapid current change is established, which shows that EMR interference in buck converter mainly occurs during the turn-off process of IGBT module. Secondly, the relationship between the aging degree of bond wires and differential mode (DM) interference signal is deduced. Thirdly, the IGBT module is equivalent to a magnetic dipole, which proves that the change of DM interference signal will cause the change of EMR signal, thus demonstrating the feasibility of using EMR signal to monitor bond wires aging. Finally, a buck converter composed of IGBT module is used as the equipment to be tested. The EMR signal is extracted by the near-field probe, and the EMR signal spectrum is used to monitor the aging degree of the bond wires. The experimental results show that with the deepening of the aging degree of bond wires, the spectrum amplitude of EMR signal increases.

1. INTRODUCTION

IGBT module is widely used in power converter because of its high switching frequency, convenient control, high input impedance, and low output impedance [1]. In general, the working environment of IGBT module is severe, which is under unbalanced electrothermal stress for a long time and prone to fatigue damage, thus reducing the reliability of the module [2]. According to statistics, about 38% of the power converter failures are caused by power devices [3]. The aging of IGBT module will not only affect the performance of power converter, but also cause system damage [4]. As one of the common packaging aging forms, the health monitoring of IGBT module bond wires aging is of great significance [5].

Higher switching speed of IGBT will make the voltage and current change rapidly, resulting in strong conducted and radiated interference [6]. The research shows that the electromagnetic interference (EMI) signal can be used as electrical parameters for aging monitoring like on-state voltage drop, on-state resistance, threshold voltage, and gate voltage overshoot [7]. The aging degree of the bond wires will change the stray inductance of the gate circuit, so it will have a great impact on the turn-on gate voltage in front of the Miller platform. The overshoot of the turn-on gate voltage of the IGBT module can be used to monitor the aging degree of the bond wires [8]. However, in order to obtain accurate turn-on gate overshoot voltage, a complex circuit needs to be designed to extract it, which is both difficult and expensive to implement. In [9], the method of bond wires aging monitoring based on on-state voltage is studied. However, the method is not very sensitive when the bond wires aging is low.

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* Corresponding author: Mingxing Du (dumx@tjut.edu.cn).
[1] Tianjin Key Laboratory of Control Theory & Applications in Complicated System, Tianjin University of Technology, Tianjin, China. [2] Department of Electrical Engineering, Technical University of Denmark, Lyngby, Denmark.

In [10], on-line aging monitoring of the bond wires of IGBT module is achieved by adding sensors and resistors to the module package and monitoring their voltage changes. However, this method needs to modify the internal wires of the IGBT module, which is impractical and too complicated. In [11], the bond wires aging is monitored using short-circuit current. However, this method requires changing the gate drive voltage, making the drive circuit more complex. In [7], the peak value of DM interference signal generated during the turn-off process of the IGBT module is used to monitor the aging degree of the bond wires of IGBT module. On the one hand, the aging fatigue of bond wires of IGBT module can be directly monitored without considering the effect of module junction temperature; on the other hand, on-line monitoring can be realized without destroying the package of IGBT module. However, in practical application, the amplitude measurement of DM interference signal usually needs expensive equipment such as EMI analyzer, which increases the monitoring cost and reduces the practicability of this method. In [3], the IGBT chip is simulated as an electric dipole and transmits the EMR signal to the space. When the EMR signal is captured by the near-field coil, different operation states of the chip can be judged according to the difference of the interference signal. Using EMR signal to monitor the health of IGBT module not only reduces the number of sensors, but also compresses the equipment space, and does not destroy the package of IGBT module. In [12], the near-field EMR signal of the DC bus is collected by the external antenna to identify the faulty devices in the power converter. This method does not need to connect or modify the additional hardware circuits of the power converter, which makes it a cost-effective fault diagnosis method for power converters. In summary, EMR signals used to monitor the internal faults of the IGBT module can reduce the monitoring cost, reduce the monitoring difficulty, and improve the monitoring sensitivity. In this paper, the relationship between the aging degree of bond wires in IGBT module and EMR signal is studied, and a monitoring method of the aging degree of bond wires in IGBT module based on the spectrum characteristics of EMR signal is proposed.

The other parts of the paper are as follows. In Section 2, the turn-off process of IGBT module is analyzed, and the behavior model of IGBT chip is obtained; the influence of bond wires aging on DM interference signal in IGBT module is analyzed, and the conclusion that DM current increases with the aging degree of bond wires is obtained; the influence of DM interference current on EMR signal is studied, and the change law of bond wires aging and EMR signal is obtained. In Section 3, the conclusion that the frequency spectrum of EMR signal increases with the deepening of bond wires aging is verified by experiments. The last part is the conclusion.

2. EFFECT OF BOND WIRES AGING ON EMR SPECTRUM

In practical application, the schematic diagram of buck converter in continuous mode is shown in Fig. 1 [13]. With the increase of the switching speed and frequency of the IGBT chip, the fast switching behavior will lead to rapid changes in voltage and current, resulting in stronger EMI. The higher di/dt

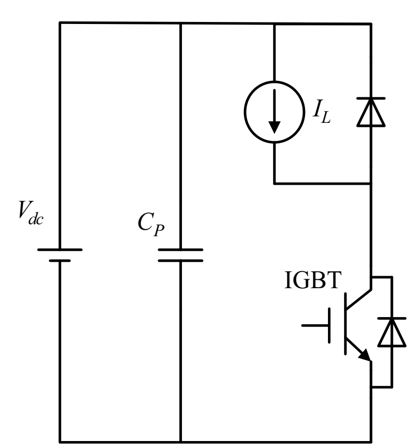

Figure 1. Schematic diagram of buck converter.

is coupled with the parasitic parameters of the IGBT module itself and line parameters, resulting in DM interference. When the parasitic parameters of the IGBT module change, it will undoubtedly lead to the change of DM interference, and the EMR signal will also change accordingly due to the influence of DM interference.

2.1. Root Reasons of DM Interference

During the turn-off process of the IGBT module, the waveforms of gate-emitter voltage, collector voltage, and collector current are shown in Fig. 2.

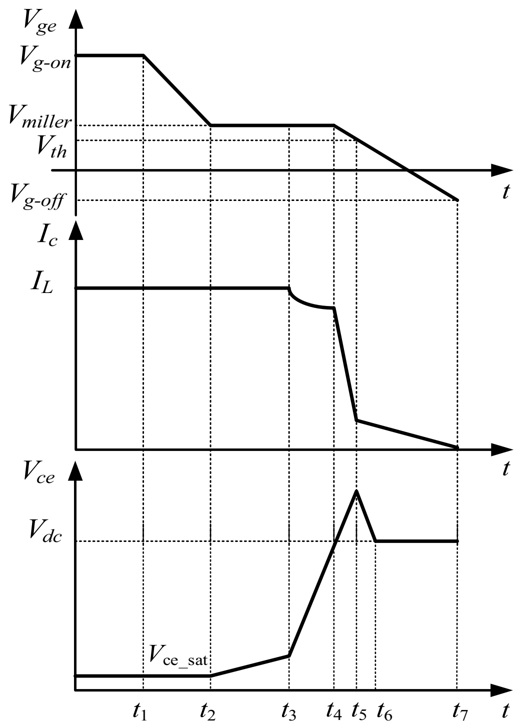

Figure 2. Voltage and current waveforms of IGBT chip during turn off process.

During turn-off process, V_{CE} rises to the bus voltage V_{dc} at time t_4, and the freewheeling diode is forward biased to provide a freewheeling path for the inductor current. Subsequently, the collector current i_c begins to decrease rapidly until a tail current begins to form at time t_5. The decreasing rate of trailing current in $t_5 \sim t_7$ stage is obviously lower than that that in $t_4 \sim t_5$ stage. The intensity of the DM interference signal is closely related to the current change rate, so the DM interference signal in the circuit in Fig. 1 is mainly generated by the rapidly decaying collector current in the $t_4 \sim t_5$ stage. At this time, the EMR signal strength generated by the circuit will also reach the maximum value [3]. During the turn-off process, the change rate of collector current depends on the carrier concentration of its internal channel, and the rapid change rate of collector current is shown in (1) [14].

$$\frac{dI_C}{dt} = \sqrt{\frac{2I_C}{(1-\alpha_{pnp})}\,\mu C_{OX}\frac{W}{L}}\frac{dV_{ge}}{dt} \tag{1}$$

where α_{pnp} is the current gain of PNP transistor, μ the carrier mobility, C_{OX} the oxide capacitance, W the MOSFET channel width, and L the MOSFET transistor channel length.

Before the rapid decline of the collector current, the gate parasitic capacitance has completed the discharge, so V_{ge} and V_{th} are not affected by the temperature change during the $t_4 \sim t_5$ stage, and dV_{ge}/dt is not affected by the temperature change during the IGBT chip turn-off process. The variation of collector current with time during the $t_4 \sim t_5$ stage is shown in (2) [2]:

$$i_c(t) = I_L - \frac{dI_C}{dt} t \ (t_4 \leq t \leq t_5) \tag{2}$$

The behavior model of IGBT chip in the stage of rapid current decline can be equivalent to a time-varying current source with parasitic capacitance [7, 15], as shown in Fig. 3.

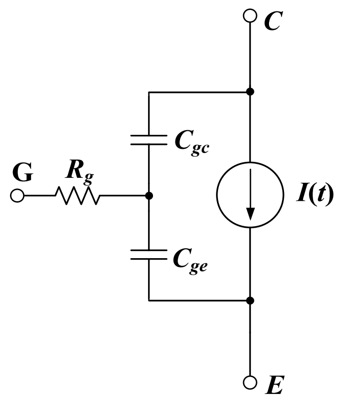

Figure 3. Behavior model of IGBT chip.

In Fig. 3, R_g is the gate parasitic resistance, C_{gc} the parasitic capacitance between the chip collector and the gate, and C_{ge} the parasitic capacitance between the gate and the emitter.

2.2. Bond Wires Aging Analysis

High-power IGBT modules are generally packaged by bond wires, and the freewheeling diode, collector terminal, emitter terminal, and IGBT chip inside the IGBT module are connected to the copper layer on the DBC through bond wires. Due temperature fluctuations, different materials are exposed to different thermal stresses, and long-term stress accumulation can lead to bond wires aging. The IGBT module emitter is subjected to the largest current density and current fluctuation, which makes the emitter

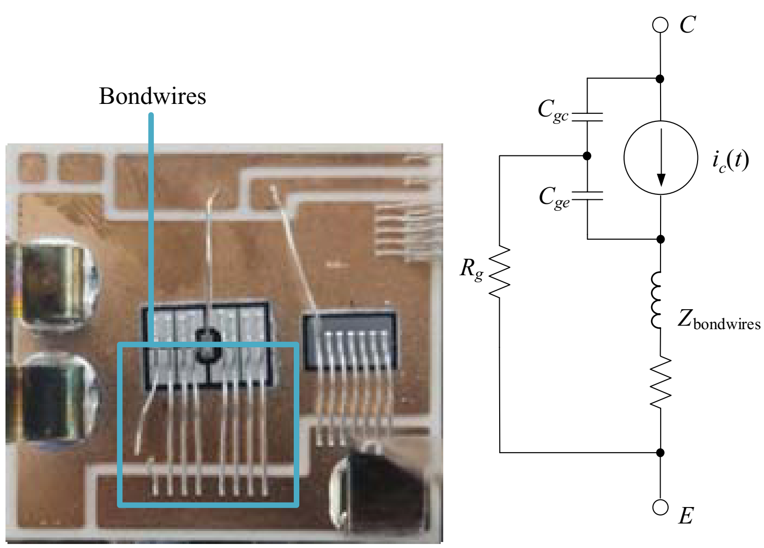

Figure 4. Circuit diagram of IGBT module. (a) Internal circuit, and (b) equivalent circuit.

bond wires more fragile than other parts, so the bond wires between the emitter and the copper layer on the DBC is the most common. The structure diagram and equivalent circuit diagram of the lift-off bond wires in the IGBT module are shown in Figs. 4(a) and (b).

In Fig. 4(b), R_g is the gate resistance, $Z_{\text{bondwires}}$ the bond wires impedance, which is determined by the aging degree of the bond wires, and the impedance increases with the aging degree of the bond wires. $i_c(t)$ is the current in the fast falling stage of the collector. During the switching process of the IGBT module, 8 parallel bond wires can be equivalent to a variable impedance. When the bond wires lift off, the impedance between the IGBT chip and emitter terminal increases. According to Norton's Equivalent Theorem, the IGBT module can be equivalent to the parallel connection of the equivalent impedance formed by the internal parasitic parameters and bond wires impedance and the equivalent current source [7, 8]. The Norton's equivalent circuit diagram is shown in Fig. 5.

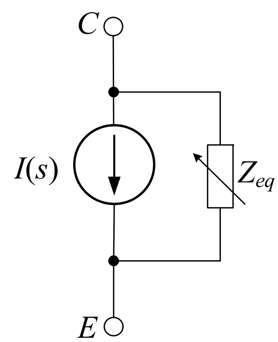

Figure 5. Norton equivalent circuit of IGBT module.

Where Z_{eq} is the equivalent impedance of the double terminal network after the current source is set to zero, as shown in (3).

$$Z_{eq} = \frac{1}{j\omega C_{gc}} + \frac{R_g\left(\dfrac{1}{j\omega C_{ge}} + j\omega Z_{\text{bondwires}}\right)}{R_g + j\omega C_{ge} + Z_{\text{bondwires}}} \tag{3}$$

2.3. EMR Signal

EMR is caused by the air propagation of DM conducted interference and common mode (CM) conducted interference. The DM conduction current loop and CM conduction current loop act as antennas to

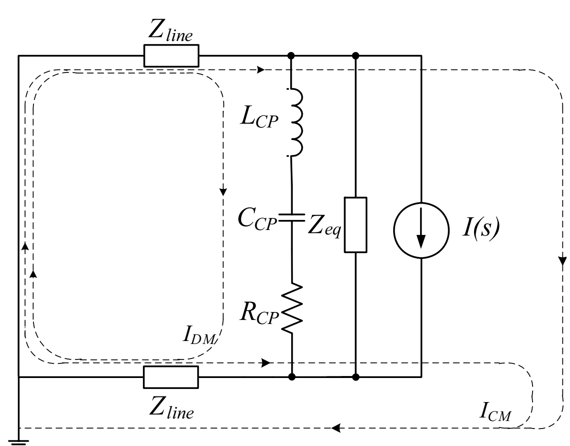

Figure 6. Conducted EMI equivalent circuit of buck converter.

radiate EMR signals into the surrounding space. Therefore, similar to conducted EMI, EMR signal is also divided into CM EMR signal and DM EMR signal. The conduction interference path in the buck converter composed of IGBT module shown in Fig. 1 is shown in Fig. 6, where I_{DM} and I_{CM} represent the DM conduction interference current and CM conduction interference current, respectively. The CM conduction interference is mainly caused by the coupling of the rapidly changing du/dt of the IGBT module and the parasitic capacitance. The DM conduction interference is mainly caused by the coupling of the rapidly changing di/dt of the IGBT module and the stray inductance, and the aging of the bond wires of the IGBT module mainly affects the stray inductance of the module. Studies have shown that with the deepening of the aging degree of the bond wires of the IGBT module, the amplitude of the DM interference signal spectrum increases [7], which leads to the change of the DM EMR signal.

According to the analysis of the equivalent circuit of DM conducted interference, the DM EMI current is shown in (4). With the increase of the number of life-off bond wires, the equivalent impedance of IGBT module increases, so does the DM EMI current.

$$I_{DM} = \frac{Z_{CP} Z_{eq}}{(2Z_{line} Z_{CP} + Z_{CP} Z_{eq} + 2Z_{line} Z_{eq})} I(s) \tag{4}$$

2.4. IGBT Module as a Magnetic Dipole

The DM EMR signal is generated by the loop formed by the wires that transmit current in the circuit, so the loop can be equivalent to a small loop antenna that can generate a radiated magnetic field. For the small antenna with loop area S_{DM} and current I_{DM}, the electric field E_{DM} at the distance from r_{DM} in free space is shown in (5).

$$E_{DM} = 1.31 \times 10^{-14} \times \frac{f^2 I_{DM} S_{DM}}{r_{DM}} \tag{5}$$

It can be seen from (5) that the radiation intensity of DM EMR is positively correlated with frequency, DM current, and loop area.

As the most basic idealized EMR unit, the magnetic dipole is shown in Fig. 7. The DM EMR signal generated by buck converter is mainly caused by I_{DM}. According to the principle of electric field equivalent source, EMR interference source can be replaced by equivalent magnetic dipole. The EMR path is usually divided into three regions: induced near field region, radiation near field (Fresnel) region, and far field region. Compared with the far field, the near field contains more properties related to the radiation source. In the radiation field, the electric field and magnetic field are orthogonal to each other, and the near field parameters can be predicted.

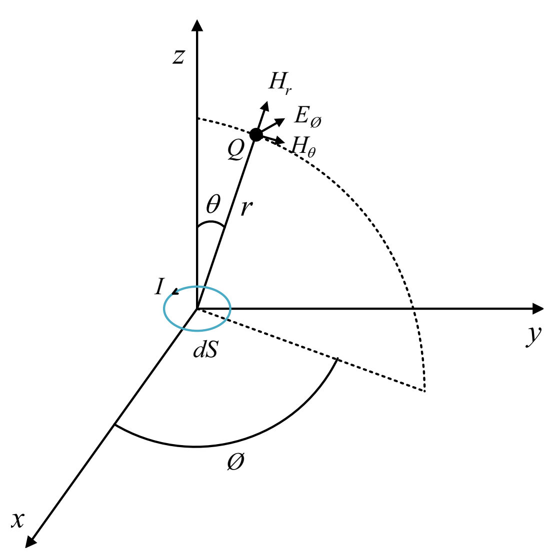

Figure 7. Radiated electromagnetic field of magnetic dipole.

The radiated electric field and magnetic field intensities of a point Q in the radiation near-field region are shown in (6) and (7) [16]. E and H represent the electric field intensity and magnetic field intensity of point Q, respectively.

$$E = \frac{IdS\beta^4}{4\pi\omega\varepsilon_0}\left(\frac{1}{\beta r} - \frac{1}{j\beta^2 r^2}\right)\sin\theta e^{-j\beta r} \tag{6}$$

$$H_\theta = \frac{IdS\beta^3}{4\pi}\left(-\frac{1}{\beta r} - \frac{1}{j\beta^2 r^2} + \frac{1}{\beta^3 r^3}\right)\sin\theta e^{-j\beta r}$$

$$H_r = \frac{IdS\beta^3}{2\pi}\left(-\frac{1}{j\beta^2 r^2} + \frac{1}{\beta^3 r^3}\right)\cos\theta e^{-j\beta r} \tag{7}$$

It can be seen from (6) and (7) that E and H of point Q at a certain point in the radiation field are related to the current and distance. dS is the area of the current loop, β the wave number, and r the distance from Q to the antenna. In this paper, I is the DM conducted interference current of the IGBT module. It can be seen from (4), (6), and (7) that with the deepening of the aging degree of the bond wires, the DM conduction interference current increases; the DM EMR signal intensity increases; and the EMR signal spectrum amplitude increases.

3. EXPERIMENTAL VERIFICATION

3.1. Experimental Platform

In order to verify the relationship between the aging degree of the bond wires and the amplitude of the EMR signal, a test platform is built, as shown in Fig. 8. A high-power DC power supply is used to provide DC voltage. The WGL100B65F23 650 V/100 A IGBT module is selected as the research device. A SEMIKRON SKKD 100/16 diode is employed as a freewheel diode (FWD). A thin film capacitor with $C_p = 490\,\mu\text{F}$ is paralleled at both the ends of the DC power supply to improve the power supply quality of the DC power supply. An Agilent MOS-X 2024A oscilloscope is utilized to capture the waveforms. A GWINSTEK DC voltage source is employed to power the customized IGBT driver board. An Agilent 33500B signal generator provides pulse width modulation (PWM) signal for the driver board. The RIGOL NFP-3 magnetic field probe is used to capture the near field signal of the IGBT module. The Tektronix RSA306B spectrum analyzer is connected with the near-field probe to record the EMR signal spectrum of the IGBT module, and the spectrum analyzer is connected to the computer to transmit the experimental data synchronously to the computer.

As can be seen from Fig. 8, the EMR signal generated by the buck converter composed of IGBT modules is captured by the magnetic field probe and converted into an electrical signal, and the signal is transmitted to the spectrum analyzer through the cable, and the spectrum analyzer imports the interference signal into the computer. Convert to visualized EMR signal spectrum by corresponding software. Comparing the difference between the EMR signal spectrum in the buck circuit before and after the aging of the bond wires of the IGBT module, the aging state of the bond wires of the IGBT module is judged.

3.2. Effects of Bond Wires Aging on EMR Spectrum Signals

In order to study the parameter characteristics of IGBT module after the failure of bond wires, a reasonable method is needed to accelerate the aging process of bond wires. The methods of power cycling test and cutting-off bond wires are widely utilized to simulate the aging state of the IGBT module. The power cycling test method is very time-consuming and difficult to implement. Fortunately, the method of cutting-off bond wires can simulate different aging degrees by cutting-off the number of bond wires, which can directly reflect the failure situation, not only can save the experimental time, but also can focus on the bond wires aging and avoid the impact of other types of faults [17]. In addition, the bond wires lift-off is an important form of the bond wires aging, and its essence is the partial disconnection of the connection of two materials. Therefore, the application of the method of cutting-off bond wires to the bond wires aging simulation of IGBT module has no effect on the condition monitoring scheme proposed in this paper.

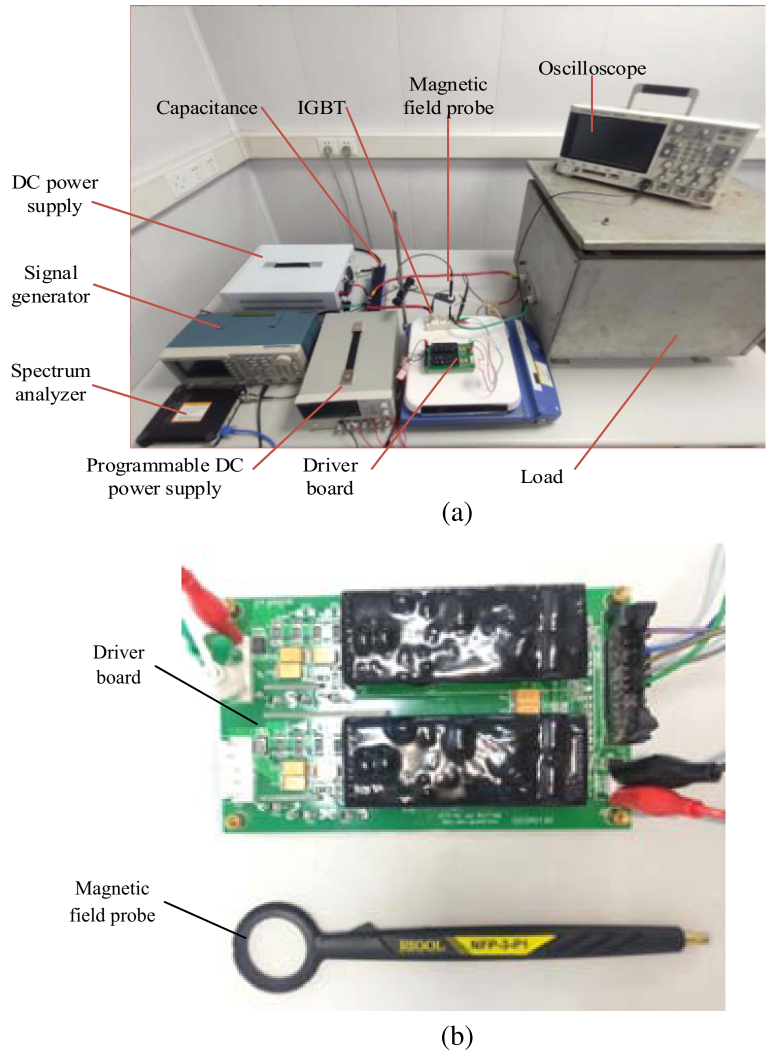

Figure 8. Experimental platform. (a) Physical connection. (b) Driver board and magnetic field probe.

When $U_{dc} = 40\,\text{V}$, the switching frequency is 40 kHz, and the duty cycle is set to 50%. The measured EMR signal spectrum of the IGBT module bond wires under different aging degrees is shown in Fig. 9.

Studies have shown that the frequency domain range of EMR in the turn-on stage of the IGBT module is usually within 10 MHz, and the frequency domain range of the EMR in the turn-off stage is usually above 100 MHz [3, 18]. The EMR generated during the turn-off process not only has a larger frequency range, but also generates stronger interference signals [18]. This verifies the conclusion presented in Section 2 that the aging degree of bond wires is monitored by the EMR generated during the turn-off of the IGBT module.

In Fig. 9, n represents the number of lift-off bond wires. Fig. 9 shows the relationship between the number of lift-off bond wires and the EMR spectrum during turn-off. In the range of 30 MHz $\sim$ 130 MHz, due to the influence of high-voltage DC power supply and driver board, the relationship between the number of lift-off bond wires and the amplitude of the EMR signal is not obvious. In the range of 130 MHz $\sim$ 180 MHz, the external noise interference signal is small. The relationship between the number of IGBT module lift-off bond wires and the spectrum amplitude of the EMR signal generated during the turn-off process can be clearly seen. As the number of lift-off bond wires increases, the spectrum amplitude of the EMR signal increases. After 250 MHz, the interference signal is mainly ambient noise.

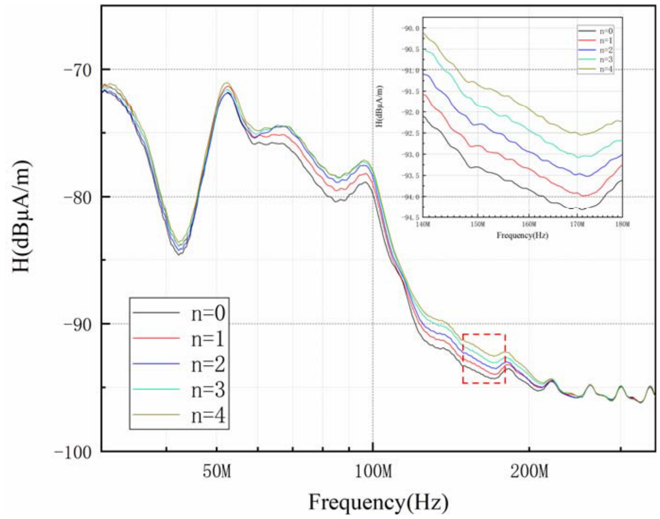

Figure 9. Relationship between the number of lift-off bond wires and EMR signal.

3.3. Condition Monitoring of Bond Wires Aging

In the actual situation, the bond wires of IGBT module lift-off due to the long-term power cycle. In order to focus on the influence of the bond wires on the EMR signal before and after the aging, the different aging degrees are simulated by cutting the number of bond wires.

In Fig. 9, in the range of 150 MHz to 170 MHz, the difference in the EMR spectrum amplitude caused by the different numbers of bond wires is relatively obvious and evenly distributed. The EMR spectrum amplitude in this frequency band is used as the basis for judging the number of lift-off bond wires. The relationship between the number of lift-off bond wires of the IGBT module and the amplitude of the EMR spectrum of randomly selected different frequency points in this frequency band is shown in Table 1.

Table 1. EMR spectrum amplitude with the number of lift-off bond wires.

n	H (dBμA/m)			
	154 MHz	156 MHZ	160 MHz	164 MHZ
	−93.548	−93.639	−93.837	−94.150
1	−93.026	−93.126	−93.340	−93.685
2	−92.517	−92.702	−92.945	−93.232
3	−92.083	−92.221	−92.436	−92.764
4	−91.591	−91.684	−91.931	−92.289

It can be seen from Table 1 that with the increase of the number of lift-off bond wires, the spectrum amplitude of EMR signal increases. According to Table 1, the relationship curve between the two can be drawn, as shown in Fig. 10.

It can be seen from Fig. 10 that in the range of 150 MHz to 170 MHz, the number of lift-off bond wires is roughly linear with the EMR signal spectrum amplitude. Each time one bond wire is lift-off, the EMR signal spectrum amplitude increases by about 0.5 dBμA. Normally, when 4 bond wires are lift-off, the IGBT module is considered to need to be replaced. Based on the relationship between the number of lift-off bond wires and the amplitude of the EMR signal, it can be seen that when the difference between the measured EMR signal spectrum amplitude and the EMR signal spectrum amplitude in the healthy state is greater than 2 dBμA, it is considered that more than 4 bond wires have lift-off, and the IGBT module needs to be replaced.

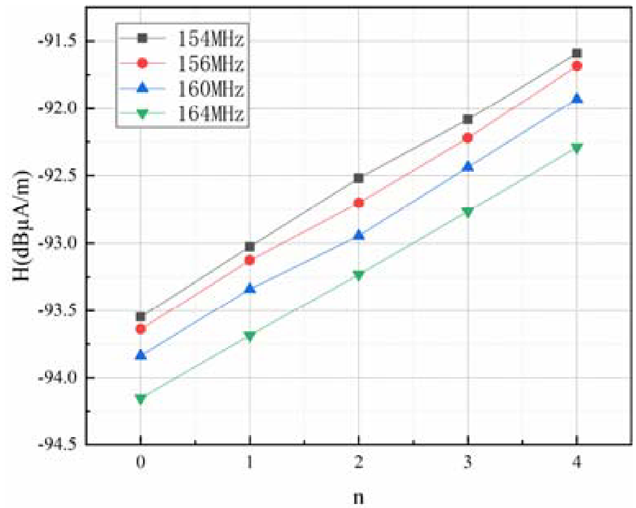

Figure 10. Relationship between the number of lift-off bond wires and the EMR amplitude at different frequencies.

4. CONCLUSION

In this paper, an aging monitoring method of IGBT module bond wires based on EMR spectrum characteristics is proposed, and the relationship between the spectrum amplitude of EMR signal and the aging degree of IGBT module bond wires is established. The change law of DM EMI current and its influence on EMR signal after the aging of IGBT module bond wires are analyzed. The conclusion that the EMR signal spectrum amplitude increases with the aging degree of the IGBT module is verified through experiments, and the critical value when the IGBT module needs to be replaced is given. In practical applications, this method only needs a set of near-field probes and a spectrum analyzer to realize online aging monitoring of IGBT module bond wires. Appropriate high-pass filter or band-pass filter will achieve better monitoring results.

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AUTHOR CONTRIBUTIONS

Zhihui Ren and Mingxing Du conceived the paper. Jinliang Yin and Chao Dong completed the experimental scheme design. Zhihui Ren and Mingxing Du analyzed the data and wrote the manuscript. Ziwei Ouyang commented on the manuscript.

DISCLOSURES

The authors declare no conflicts of interest.

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